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Attentional capture by masked colour singletons

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ABSTRACT

We tested under which conditions a colour singleton of which an observer is unaware captures attention. To prevent visual awareness of the colour singleton, we used backward masking. We find that a masked colour singleton cue captures attention if it matches the observer's goal to search for target colours but not if it is task-irrelevant. This is also reflected in event-related potentials to the visible target: the masked goal-matching cue elicits an attentional potential (N2pc) in a target search task. By contrast, a non-matching but equally strong masked colour singleton cue failed to elicit a capture effect and an N2pc. Results are discussed with regard to currently pertaining conceptions of attentional capture by colour singletons.

1. Introduction

Colour is a powerful feature for discriminating relevant from irrelevant visual objects (e.g., Hansen & Gegenfurtner, 2009). Each specific colour, however, conveys different information to an organism, conditional on what the organism actually aims to do. Accordingly, during visual search for relevant objects humans frequently exert top-down control over which colours to attend to and which to ignore (cf. Duncan & Humphreys, 1989; Green & Anderson, 1956; Wolfe, 1994; Wolfe & Horowitz, 2004).

In line with this general notion, a number of psychological experiments suggested that objects capture attention to the degree that they match a set of searched-for relevant colours. In a typical experiment, participants search for a predefined colour target and they do not know where exactly this target will be shown (Folk & Remington, 1998; Gibson & Kelsey, 1998). Two sorts of peripheral cues can then be used to indicate a target position in advance of the target. (1) Cues with a colour similar to that of the searched-for targets. These are the matching cues because their colour matches the search templates which are specified for the targets. (2) Cues with a colour dissimilar to the targets. These are the non-matching cues because their colours do not match the search templates. The cues are presented prior to the target, either at the position of the target (valid condition) or at another position than the target (invalid condition). If a cue captures attention, it will facilitate discrimination and detection of a target at the cued position relative to a target away from the cue (Posner, 1980).

In line with the concept of goal-directed attentional capture, Folk and Remington (1998) found that if cue and target positions were uncorrelated and cues therefore did not reliably inform about the target's position, (1) goal-matching colour cues captured attention, whereas (2) non-matching colour cues did not (for a review, see Burnham, 2007). Goal-matching cues created a validity effect, with faster responses to validly than to invalidly cued targets while non-matching cues did not. The results were found although both top-down matching and non-matching colour cues were equally "salient": both of these cues were so-called colour singletons. This means that all cues had an individuating colour by which they stood out against a background consisting of homogeneously coloured alternative stimuli.

Yet, even a non-informative and task-irrelevant colour singleton can capture attention in a stimulus-driven way (cf. Burnham & Neely, 2008). This has advantages, too. An irrelevant colour that attracts or captures attention has the power to overcome the pertaining goal settings. Thus, stimulus-driven attentional capture allows switching to a more adaptive behaviour (cf. Horstmann, 2002, 2005). Think of fishes like sticklebacks, or birds like ruffs. These species have different colours during mating and non-mating phases. As a consequence of stimulus-driven capture by irrelevant colour singletons, an animals' mating gown could interrupt mating-unrelated behaviour in an on-looking con-specific so that the onlooker could switch to more adaptive courting behaviour on instance of seeing the unanticipated mating gown colour. Such advantages of attending to task-irrelevant colours are one reason

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why local feature contrast (as realised in colour singletons) has been regarded to capture attention in a stimulus-driven manner (cf. Bergen & Julesz, 1983; Itti & Koch, 2001; Parkhurst, Law, & Niebur, 2002).

The exact way in which stimulus-driven capture interacts with top-down contingent capture by non-informative colour singletons is not yet fully understood. Two general principles have been advocated to explain the interaction (cf. Reynolds, Chelazzi, & Desimone, 1999; Serences et al., 2005). First, top-down control could be achieved by top-down contingent capture (Folk, Remington, & Johnston, 1992). This means that an observer can set up a template to search for a particular colour (or in general a particular feature) in advance of visual stimulation (Ansorge & Horstmann, 2007; Duncan & Humphreys, 1989). Thus, attention could be biased toward relevant template-matching features right from stimulus onset (e.g., Bichot, Rossi, & Desimone, 2005).

Secondly, top-down control over attention to colour singletons could be occurring after an initial phase of stimulus-driven attention (cf. Kim & Cave, 1999; Ogawa & Komatsu, 2004; Wolfe, 1994). With respect to colour, this means that attention would be initially driven by a local colour difference in an image (cf. Itti & Koch, 2001) or by local colour salience (cf. Donk & van Zoest, 2008; Theeuwes, 1992, 1994). Only after initial capture took place, participants might be able to selectively ignore the irrelevant stimuli (Belopolsky, Schreij, & Theeuwes, 2010; Theeuwes, Atchley, & Kramer, 2000).

Note that according to this view, colour contrast or colour salience is defined in merely objective or algorithmic terms only: it is determined by a measured local "colour difference" between stimulus and surround or between one singleton stimulus and several non-singleton stimuli. This algorithmic definition is typical of modelling approaches. For example, a colour difference could be measured as the standard deviation within a circumscribed region of the image (cf. Frey, Honey, & König, 2008).

However, colour salience could be used in a more refined sense as referring to the subjective representation of such a colour difference. Under this perspective, a local colour difference is a favourable if not even a crucial prerequisite of stimulus-driven capture. Yet, a mere local colour difference would not be sufficient for stimulus-driven capture. In addition to a high colour difference, participants would need to be aware of this colour difference for its stimulus-driven capture.

In the present study, we tested the influence of awareness on stimulus-driven and top-down contingent attentional capture by non-informative colour singletons. We used singleton colour cues with a top-down matching or a non-matching colour. We prevented our participants' awareness of the singleton colour cue to large extents by backward masking of the cue (cf. Breitmeyer, Ro, & Singhal, 2004; Schmidt, 2002). Our expectations were as follows. First, if a colour singleton captures attention independently of awareness as implied by computational theories of feature-driven attention (cf. Parkhurst et al., 2002), we should find attentional capture by invisible colour singleton cues. Importantly, there is evidence that a colour singleton remaining outside of the awareness of an observer can capture attention if task relevant (Kristjánsson, Vuilleumier, Malhotra, Husain, & Driver, 2005; Scharlau & Ansorge, 2003; Woodman & Luck, 2003).

Secondly, however, whether or not stimulus-driven capture by colour singletons depends on awareness has not been tested so far. For instance, in Kristjansson et al.'s (2005) study, participants searched for singletons. Therefore, the invisible colour singletons in that study could have captured attention in a top-down contingent fashion or in a stimulus-driven way. If attentional capture by colour singletons outside awareness is stimulus-driven there should be evidence for attentional capture for both goal-matching and non-matching colour singleton cues in the present experiment.

In addition to a behavioural validity effect of the cues, we recorded N2pcs elicited by the masked cues. The N2pc is a stronger negative event-related potential (ERP) component at posterior scalp sites contra- than ipsilateral of an attended stimulus (cf. Luck & Hillyard, 1994). Of importance in the present context: the N2pc provides a window into the time course of the attentional effect. It is, thus, a more exhaustive measure of attention than the behavioural cueing effect. Specifically, the N2pc allows us to find evidence to tell the two forms of top-down control apart that we introduced above. If a rapid suppression of a non-matching singleton colour cue takes effect only after initial stimulus-driven capture by such a singleton cue (cf. Theeuwes et al., 2000), the N2pc might show evidence of this initial capture even where no behavioural cueing effect is seen in the RTs (cf. Ansorge & Heumann, 2006). Stimulus-driven capture reflected in the N2pc would than quickly fade and as a result no cueing effect would be found in the RTs to the targets.

2. Experiment 1

One of the tasks of our participants was to search for a visible colour-defined target and to report its shape. Search for a particular colour was enforced by presenting only one visible colour target and several visible differently coloured distractors per trial. Thus, the visible targets were non-singletons and our participants were forced to search for a colour to find this target. Singleton search was not an option for finding the target. As a consequence, any capture effect of the non-matching and non-predictive colour singleton cue under these conditions must be stimulus-driven.

The participants' awareness of the cues was diminished by backward masking of the cues (Breitmeyer, 1984; Breitmeyer & Ogmen, 2006; Klotz & Wolff, 1995). In addition to the target search task to assess the cueing effect we used cue detection as a second task for verifying the participants' low awareness of the masked cues. The two tasks of searching for the visible target and detecting the masked singleton colour cue were integrated into one block: we asked our participants to withhold their response if they saw a matching colour singleton cue preceding the target display and to only respond to (the shape of) the searched for visible colour target if they did not see a matching singleton colour cue before the target. In this way, we can eliminate all trials from the target search task in which the participants correctly reported the presence of the goal-matching singleton colour cue (cf. Bridgeman, Kirch, & Sperling, 1981; Ivanoff & Klein, 2003).

Based on the number of trials in which participants did not respond, we were also able to assess the cue's visibility in general. Because trials in which participants did not respond indicated that the participants believed that they had seen the matching cue, non-response trials where actually a matching cue was shown were taken as "hits", while non-response trials where a non-matching cue was shown were taken as "false alarms (FAs)" in the sense of signal detection theory (SDT; cf. Green & Swets, 1966). The probabilities of hits and FAs were then compared to one another in form of SDT's effect-size measure d' (Green & Swets, 1966; Macmillan & Creelman, 2005). This measure becomes zero for chance performance and can become infinitely large with an ever increasing number of correct responses. The measure d' is recommended to assess residual stimulus visibility because of its high sensitivity (cf. Klotz & Neumann, 1999; Reingold & Merikle, 1988).

Note that under the present conditions, the target search task requires that the participants maintained a particular colour-search mode. In addition, the participants' successful performance of finding a visible colour target in each trial also reinforces this search mode and thus motivates the participants to maintain their goal setting of searching for the target's and the matching cue's

colour. In this respect, the current cue-detection task is more sensitive for residual cue perception than having participants search for a visible colour target in one block and for a masked colour singleton in another: in the latter conditions, it could well be that participants give up a search set for a particular colour because this search set is not successful in at least part of the trials (cf. Ansorge, Kiss, & Eimer, 2009).

Of course, we had to inform our participants about the presence of the masked colour singleton cue in advance. For that purpose, we illustrated the sequence of events by means of a slow-motion of the trials. We took advantage of this sort of advance information, too, to test the cue's visibility in yet another way: we carefully avoided informing our participants about the probability of the different masked cues. This allowed us to assess singleton colour cue visibility by additionally looking at the frequency of the participants' nogo responses. If the participants saw the masked matching singleton colour cue they should have adjusted their nogo rate to the objective probability of $p = .5$ of the matching cue. However, in light of prior findings showing little learning of or adaptation to the probabilities of different kinds of masked stimuli (cf. Ansorge, Heumann, & Scharlau, 2002; Cheesman & Merikle, 1985), we expected a low fit between the nogo response rate and the rate of matching singleton colour cue trials if our participants were not aware of the cues. Specifically, we expected that many participants' nogo trial rates would correspond to their low frequency of perceiving a matching cue. Therefore, the participants' nogo rates should be lower than the objective probability – that is, nogo rates should be shifted in the direction of a lower limit of $p = 0$. The objective $p = .5$ in contrast was likely an upper boundary of the nogo rate.

The expected low visibility of the cues notwithstanding, we expected that at least the matching colour singleton cue captured attention. To test for this possibility, we also measured the N2pc elicited by the masked singleton cue under two conditions: with a matching and with a non-matching colour cue. If participants attend to the singleton cue, the cue-elicited contralateral activity should be more negative than the ipsilateral activity.

In addition, if the masked singleton colour cue captured attention, we also expected a behavioural cueing effect in the responses to the visible target's shapes. Responses should be facilitated in valid as compared to invalid conditions. This cueing effect should be observed at least with the matching colour singleton cue (cf. Ansorge et al., 2009). In addition, if stimulus-driven singleton capture is independent of the participants' awareness of the singleton, we should also find a behavioural cueing effect in the non-matching conditions.

A final purpose of the present experiment was to test the influence of the response relevance of the masked cue. To that end, both matching and non-matching cues were either congruent or incongruent with the target shape. Because our participants had to respond to the target shape, a shape congruent cue also indicated the correct response, while a shape incongruent cue indicated the incorrect response. Prior research demonstrated that masked stimuli can activate responses (cf. Klotz & Neumann, 1999; Neumann & Klotz, 1994). If response activation can occur independently of attentional capture we should find a congruence effect, with faster responses in congruent than incongruent conditions. Yet, if response activation requires a prior shifting of attention toward a subliminal stimulus, the congruence effect could be restricted to those cues (e.g., the matching cues) that happened to capture attention.

Going one step further, in visual search conditions with a relatively high spatial uncertainty about the target position, response activation could only be possible during a recurrent processing phase – that is once participants become aware of the singleton. Hamker (2005), for example, thinks that during visual search, response activation is only possible after attentional capture in a phase when activity from the frontal eye fields feeds back on activity further down stream the cortical hierarchy in area V4. On the basis of this theory one could therefore argue that under visual search conditions, response relevance of a masked visual stimulus does not matter because response activation is only possible once the observer becomes aware of the singleton during recurrent processing. This possibility is entailed by theories linking visual awareness to the phase of feed-back or recurrent visual processing (cf. Lamme & Roelfsema, 2000). In line with this possibility, Scharlau and Neumann (2003), for example, failed to find a response activation effect of masked cues under visual search conditions when the display contained more than two visible distractors. This was found although Scharlau and Neumann (2003) used masked stimuli that matched the participants' target templates and that had strong response activation effects under conditions with only few distractors and with low spatial uncertainty about the target position (cf. Klotz, Heumann, Ansorge, & Neumann, 2007; Klotz & Wolff, 1995).

2.1. Method

2.1.1. Participants

Twelve volunteers (7 female) with a mean age of 24 years participated.

2.1.2. Stimuli and procedure

See Fig. 1. A small rectangular fixation aid was shown in the centre of the screen throughout each trial. Four angular cues (side length 1.3°) were shown for 17 ms (corresponding to 1 refresh of the computer screen) and four angular backward masks (side length of 1.6°) were presented for 200 ms with an stimulus onset asynchrony (SOA) between cues and masks of 51 ms. All stimuli had an eccentricity of 4.3° and were shown one per each corner on the four corners of a virtual rectangle (centred on the screen, with its sides parallel to the monitor edges). Because of the brief SOA and the masks' inner contour surrounding the outer contour of the cues, the cues were backward masked by metacontrast masking (cf. Breitmeyer, 1984; Breitmeyer & Ogmen, 2006).

In each trial, two of the cues were squares and two were diamonds. The same was true of the masks. In congruent trials, all four cues had the same shapes as the subsequent masks at their respective positions. In incongruent trials, all four cues had a different shape than the masks at their respective positions. The visible target was defined by its colour: in each trial, only one of the clearly visible masks was shown in a pre-specified colour that was known to the participants. This was the target. Different target colours were used, balanced across participants (with CI chromaticity x/y coordinates in brackets): red (.619/.333), green (.295/.579), brown (.439/.470), and purple (.276/.138). The other three masks in each trial were presented each in a different colour, drawn randomly from the set of remaining colours plus grey (.288/.311). As a consequence, the targets were non-singletons, and participants had to maintain a top-down search setting for a particular colour to find the targets. Participants had to respond to the target's shape. They had to press the left key for a diamond and the right key for a square, or vice versa, with different target-response mappings balanced across participants.

In each trial, one of the cues was a colour singleton. The singleton cue was matching if it had the target's colour. It was non-matching if it had one of the remaining non-target colours. The colours of the non-matching and matching cue, respectively, were chosen in advance of the experiment and fix throughout the experiment. In each trial, the colours of the remaining masked cues were all the same, with that colour chosen randomly from the set of the remaining colours but independently from the selection of the

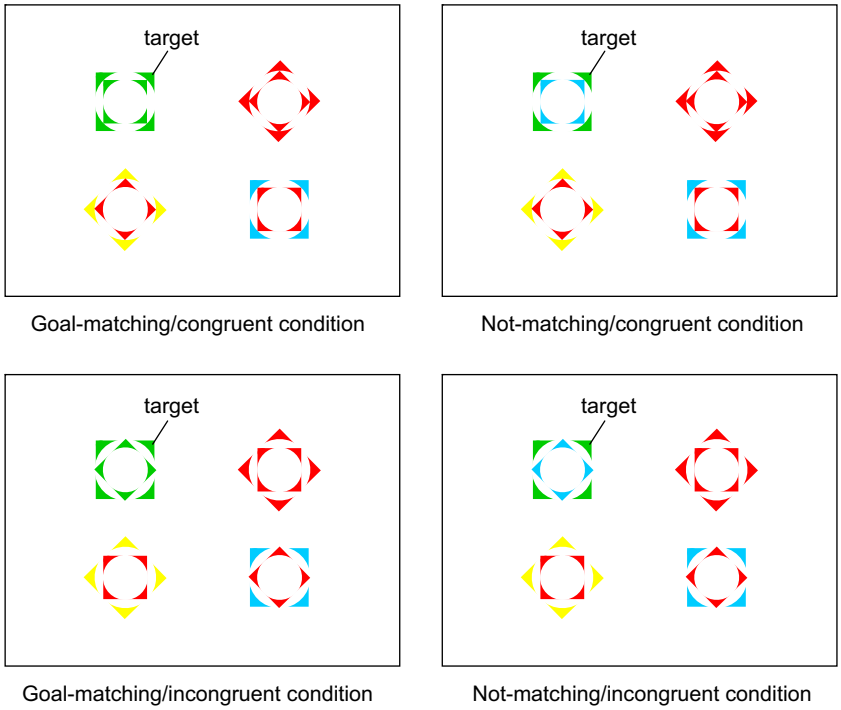

Fig. 1. Depicted are examples of valid trials with colour singleton cue and target (here: the larger green stimulus) at the same position as the cue, with a goal-matching cue (left) or a non-matching cue (right), and congruent cues at the top or incongruent cues at the bottom of the figure. The larger stimuli were the masks, only one of which was the target defined by its specific colour. The smaller stimuli were the cues, one of which was a colour singleton cue. Cues and masks were presented in successive displays. This created backward masking of the cues. Therefore, participants were not aware of the cues. For further details refer to the method section. Stimuli are not drawn to scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mask colours. Thus, there was a colour singleton cue in each trial. Matching colour singleton cues were presented in half of the trials, and non-matching colour singleton cues were presented in the other half of the trials. The positions of singleton cue and of colour target were uncorrelated. As a result, we got 25% valid and 75% invalid conditions.

Participants searched concomitantly for the predefined singleton cue and the colour target. If they saw a goal-matching cue (i.e., a colour singleton that had the target defining colour), they had to refrain from responding. Only if they did not see a matching cue, they had to report the colour target shape by pressing the left key for a diamond and the right key for a square, or vice versa (balanced across participants). Prior to the experiment, the task was carefully explained to the participants, with the stimulus sequence being shown in slow-motion to explain what a matching cue looked like.

Participants worked through 16 blocks. Each contained 64 trials in a random sequence resulting from two repetitions of each of the combinations of the two singleton cue colours × four singleton cue positions × two target positions × two target shapes.

2.1.3. EEG recording and analysis

Horizontal EOG (electrooculogram) and EEG (electroencephalogram) were DC-recorded with Ag/AgCl electrodes from 27 sites, with impedances kept below 5 kΩ, and a sampling rate of 250 Hz. The low-pass filter was set to 40 Hz. The left ear was used as an online reference and the data were offline re-referenced to an average across left and right ear. Trials with saccades (voltage > ±30 μV in HEOG), eye blinks (voltage >±60 μV at FPz), and muscle artifacts (voltage > ±80 μV at any electrode) were excluded. ERPs were calculated for 500 ms, that is, for 400 ms after the cue with respect to baseline activity in the 100 ms prior to the cue. The mean amplitude of the cue-elicited N2pc was recorded in a time window from 200 to 260 ms after cue onset at PO7 and PO8. These are the time window and electrode positions that have been used by Ansorge et al. (2009). Mean amplitudes of target-elicited contra-to-ipsilateral activity at PO7 and PO8 during an early (140–200 ms after the cue) and a late time window (200–260 ms after the cue) were additionally calculated and analysed. This analysis was restricted to trials in which participants failed to report the singleton cue.

2.2. Results

2.2.1. Search for visible target singletons

See also Figs. 2 and 3 for the go responses. Out of all trials, less than 1.0% was rejected because responses were faster than 100 ms or slower than 1500 ms. Go responses in the goal-matching conditions and in the non-matching conditions were subjected to a re-

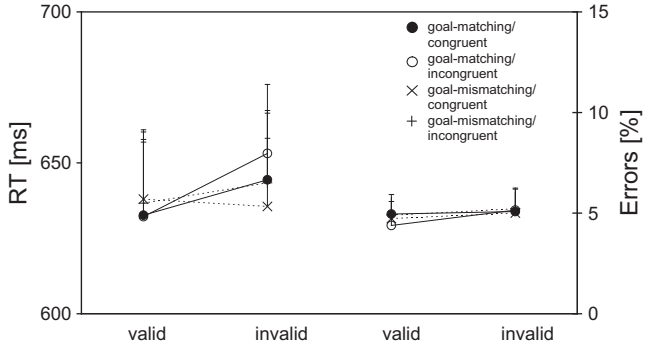

Fig. 2. Mean reaction times (RTs) on the left and mean percentages of errors on the right as a function of whether the masked singleton cue's colour matched or not matched the goals, whether the singleton colour cue had (congruent) or had not (incongruent) the same shape as the subsequent target in the same trial, and cue-target distance (valid vs. invalid). Bars depict standard errors.

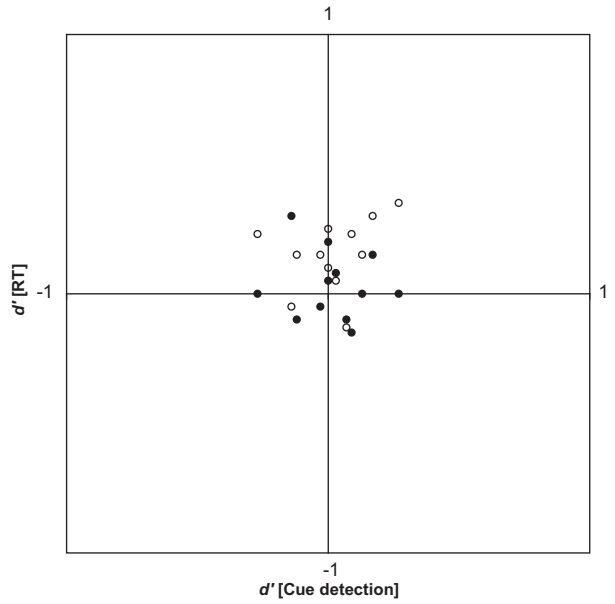

Fig. 3. Individual cueing effects in target search reaction times (expressed as d' [RT]) of the goal-matching colour cue (open circles) and of the not-matching colour cue (filled circles) as a function of cue visibility measured in a cue-detection task (expressed as d' [cue detection]) in Experiment 1 (data from 12 participants).

peated-measures ANOVA with the variables match (matching vs. non-matching), validity (valid vs. invalid), and shape congruence (shape congruent vs. shape incongruent). This ANOVA revealed a significant main effect of validity, $F(1, 11) = 10.05$, $p < .01$, and a significant match × validity interaction, $F(1, 11) = 4.83$, $p = .05$. RT was lower in valid (635 ms) than in invalid conditions (644 ms). The interaction reflected that this cueing effect was restricted to the matching conditions (valid RT = 632 ms; invalid RT = 649 ms, $t[11] = 4.59$, $p < .01$). The cueing effect was absent in the non-matching condition (valid RT = 637 ms; invalid RT = 640 ms, $t < 1.00$). All other main effects, all Fs < 1.00, and interactions, all Fs < 2.60, all ps > .13, were not significant.

No significant effects were found in a corresponding ANOVA of the arc-sine transformed error rates, all Fs < 1.00.

2.2.2. Cue detection

See Table 1 for a documentation of individual observers' data. The cue was well masked. In the majority of the trials, participants failed to report the goal-matching colour singleton cue: rates of trials in which participants did not respond were low ($M[P] = .14$; $SD[P] = .15$; range $[P] = .01 - .49$). This means that participants indeed failed to adjust their nogo rate to the rate (.5) of the masked colour singleton cue. In fact, rates of hits (no responses if a matching colour singleton cue was shown) and FAs (no responses if in fact a non-matching colour singleton cue was shown) were about equal: average d' scores were 0.03, −0.02, −0.02, and −0.03, in the valid shape congruent, valid shape incongruent, invalid shape congruent, and invalid shape incongruent conditions, respectively, and averaged across levels of shape-congruence and cue-target distance, d' was 0.02, all five ts < 1.00.

2.2.3. Cue detection and target search

To further investigate whether cue visibility could have been responsible for the validity effect, we computed four measures of the individual RT validity effects, and correlated these RT measures with the individual d' values of the detection task. If cue visibility was crucial for the RT validity effect, the corresponding correlations should be positive and significant (cf. Holender & Duscherer, 2004).

The first RT validity effect measure was d'_{RT}. It counts RTs below the median correct RT as "hits" in valid and as "FAs" in invalid conditions. The idea here is that if a singleton colour cue captures attention, it should facilitate target RTs (i.e., decrease RT below the median) in valid but certainly not in invalid conditions. The d'_{RT} score in the matching condition (corresponding to the matching singleton colour cue's capture effect) was 0.15, $t(11) = 3.69$, $p < .01$. This d'_{RT} score did not significantly correlate with a d' score derived from the Hits and the FAs concerning the masked cue's detection, $r(12) = .32$, $p = .31$ (see also Fig. 3). The d'_{RT} measure provides a fair comparison with the d' of the cue-detection task because both these measures are scaled down effect sizes of a dichotomous categorisation. However, it depends on the correct median RT as a fair representation of the distribution of the RTs.

Therefore, we additionally correlated d' from the cue-detection task with the simple RT cueing effect (invalid RT–valid RT), $r(12) = .13$, $p = .68$, with *Cohen's d* of the RT cueing effect (invalid M[RT]–valid M[RT]/SD pooled across congruent and incongruent RTs; cf. Dunlop, Cortina, Vaslow, & Burke, 1996), $r(12) = .16$, $p = .63$, and with the mean RT rank difference between correct valid and invalid RTs, $r(12) = .18$, $p = .58$. All of these measures confirmed that there was no significant correlation between singleton colour cue detection performance and RT cueing effect. See also Table 2 for the correlations between RT cuing effects and visibility scores.

Table 1
Probabilities of hits in goal-matching conditions and of false alarms (FAs) in non-matching conditions of Experiment 1, as a function of the variables singleton-cue-target distance (valid vs. invalid), singleton-cue target shape congruence (congruent vs. incongruent), and averages of the hit and FA probabilities collapsed across levels of singleton-cue-target distance and singleton-cue target shape congruence. Each row corresponds to one participant.

Goal-matching					Goal-mismatch				
Valid		Invalid			Valid		Invalid		
Congruent	Incongruent	Congruent	Incongruent	Average	Congruent	Incongruent	Congruent	Incongruent	Average
0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01
0.05	0.02	0.05	0.05	0.04	0.06	0.06	0.05	0.09	0.07
0.03	0.03	0.04	0.04	0.04	0.03	0.02	0.04	0.03	0.03
0.11	0.05	0.05	0.09	0.08	0.09	0.10	0.06	0.05	0.08
0.47	0.48	0.49	0.51	0.49	0.46	0.50	0.48	0.48	0.48
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.24	0.38	0.17	0.32	0.28	0.21	0.32	0.27	0.34	0.29
0.08	0.07	0.09	0.06	0.08	0.05	0.09	0.07	0.05	0.07
0.30	0.28	0.36	0.34	0.32	0.31	0.25	0.30	0.29	0.29
0.13	0.20	0.15	0.17	0.16	0.20	0.22	0.17	0.18	0.19
0.04	0.10	0.05	0.07	0.07	0.06	0.02	0.07	0.05	0.05
0.08	0.03	0.05	0.12	0.07	0.06	0.13	0.07	0.09	0.09

Table 2
Individual performance in cue detection (d') and the cue's RT effects during target search ($d'_{RT}s$, Cohen's d RT, RT cueing effect, and mean ranked RT cueing effect) as well as means across participants and t values (tested against null), separately for matching cues (on the left) and non-matching cues (on the right) in Experiment 1.

	d' (as non-matching)	d'RT	Cohen's d RT	RT cueing effect	Mean ranked RT cueing effect	d' (as matching)	d'RT	Cohen's d RT	RT cueing effect	Mean ranked RT cueing effect
1	0.27	0.35	0.18	26	63.21	0.27	0.00	0.08	13	12.25
2	−0.27	0.23	0.08	10	41.13	−0.27	0.00	−0.10	−11	−15.33
3	0.13	0.15	0.04	9	23.01	0.13	0.00	0.07	12	21.16
4	0.00	0.10	0.02	2	23.22	0.00	0.05	0.00	0	15.66
5	0.03	0.05	0.16	20	18.62	0.03	0.08	0.08	10	18.87
6	0.00	0.25	0.18	23	63.06	0.00	0.20	0.12	15	45.25
7	−0.03	0.15	0.25	40	35.67	−0.03	−0.05	−0.01	−1	−3.78
8	0.07	−0.13	0.00	0	−13.37	0.07	−0.10	−0.14	−24	−29.30
9	0.09	0.23	0.18	29	32.90	0.09	−0.15	−0.10	−16	−22.35
10	−0.12	0.15	0.11	24	34.33	−0.12	−0.10	−0.09	−17	−27.88
11	0.17	0.30	0.09	11	40.67	0.17	0.15	0.06	8	24.43
12	−0.14	−0.05	0.01	3	5.56	−0.14	0.30	0.18	37	42.69
Mean	0.016	0.15	0.11	16	30.67	0.016	0.031	0.01	2	6.81
$t(11)$	0.39	3.69	4.64	4.55	4.89	0.39	0.82	0.43	0.42	0.90
p	.71	.004	.001	.001	.001	.71	.43	.68	.68	.39

2.2.4. N2pc of matching cue

We tested whether the goal-matching cue elicited an N2pc. In an ANOVA with the variables laterality (contra- vs. ipsilateral of cue), side (left vs. right), and validity (valid vs. invalid cue), we confirmed the expected main effect of laterality, $F(1, 11) = 6.51$, $p < .05$, with more negative activity at cue-contralateral (−1.6 μV) than cue-ipsilateral (−1.1 μV) electrodes (see Fig. 4). The other main effects and interactions, all $ps > .11$, were not significant.

The matching cue's N2pc was only small, probably because the target was shown quickly after the cue, and cue and target positions were uncorrelated. This compromised the cue-elicited N2pc by its relative short duration (cf. Ansorge et al., 2009).

2.2.5. N2pc of non-matching cue

We tested whether the non-matching cue elicited an N2pc. In line with the lacking behavioural cueing effect, the main effect of laterality was not significant, $F(1, 11) = 1.30$, $p = .28$. Instead we found a significant laterality × validity interaction, $F(1, 11) = 39.89$, $p < .01$. This interaction reflected that the activity 200–260 ms after the cue was governed solely by the target. In valid conditions, cue and target were on the same side and target-contralateral (and cue-contralateral) negativity outweighed target-ipsilateral (and cue-ipsilateral) negativity (difference: −2.2 μV). In invalid conditions, cue and target were on different sides and target-contralateral (but cue-ipsilateral) negativity outweighed the target-ispilateral (but cue-contralateral) negativity (difference: −2.6 μV).

2.2.6. Target-elicited laterality effects with matching cues

Looking at Fig. 5, one can see that the matching cue influenced the target-elicited laterality effects before 200 ms after the cue. A two-phase pattern emerged that peaked at PO7 and PO8. We observed an earlier onset of laterality under valid conditions than invalid conditions in a window from 140 ms to 200 ms after the cue's onset. This gave way to a sharp decline of the laterality effect under valid compared to invalid conditions from beyond 200 ms after the cue. In Fig. 5, this can be seen as a crossing of the lines correspond-

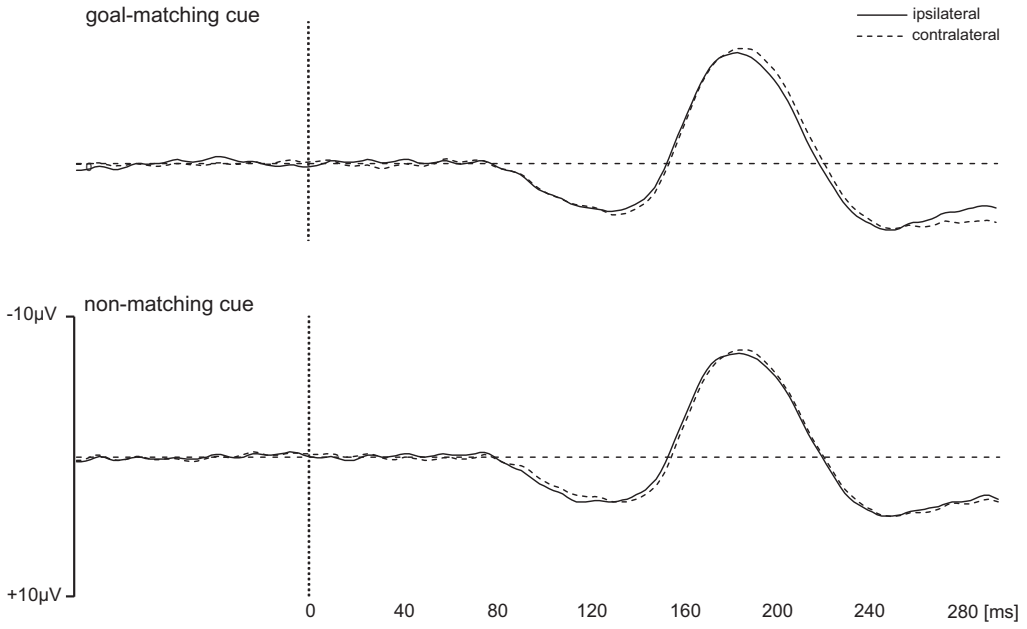

Fig. 4. Activity contralateral to the cue (dashed lines) versus ipsilateral to the cue (solid lines) at PO7 and PO8, separately for matching cues (upper panel) and non-matching cues (lower panel). ERPs are collapsed across left and right, response-congruent and response-incongruent conditions, and valid and invalid conditions. ERPs are from trials with correct responses to the target's shape. These trials were misses of the goal-matching cue that would have required withholding the response. Vertical lines at 0 ms indicate cue onset.

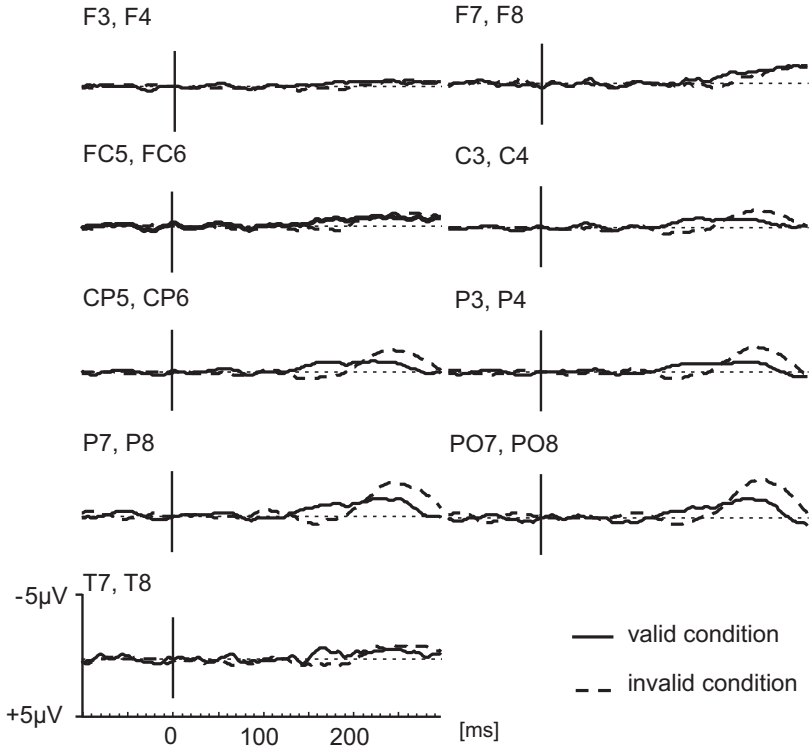

Fig. 5. Activity at electrodes contralateral to the target minus activity at electrodes ipsilateral of the target, separately for different scalp positions, matching valid cues (solid lines) and matching invalid cues (dashed lines). ERPs are collapsed across left and right, and response-congruent and response-incongruent conditions. ERPs are from trials with correct responses to the target shapes. These trials were therefore misses of the matching cue that would have required withholding the response. Vertical lines at 0 ms indicate cue onset.

ing to the target-elicited laterality effect under valid and invalid conditions, respectively.

In an ANOVA of the averages in the early phase (140–200 ms after the cue) with variables as above (but laterality defined relative to the target), we found a significant laterality × validity interaction, $F(1, 11) = 6.51$, $p < .05$. This valid to invalid difference reflected an early laterality effect elicited by the matching cue. The valid cue on the same side as the target boosted the target's laterality effect (target-contralateral–target-ipsilateral = −0.8 μV). The invalid matching cue on the opposite side of the target diminished the target's laterality effect (target contralatral–target ipsilateral = 0.3 μV). This early cueing impact was unexpected. No such effect was found in a prior study (cf. Ansorge et al., 2009).

A similar ANOVA of the later phase (200–260 ms after the cue) revealed a significant main effect of laterality, $F(1, 11) = 46.10$, $p < .01$. This indicated that by now the target captured attention. Again, an interaction between laterality and validity (reflecting the influence of the cue) was found, $F(1, 11) = 6.16$, $p < .05$. The target-elicited N2pc was smaller under valid (contralateral activity–ipsilateral activity = −1.8 μV) than under invalid conditions (contralateral activity–ipsilateral activity = −2.7 μV).

Describing the sequence from early to late phases in the matching conditions, capture (as a laterality effect) was elicited by any top-down matching colour stimulus, be that the matching colour cue (reflected in the early phase's laterality × validity interaction) or the target (reflected in the later phase's laterality effect). The valid cue's capture towards the finally relevant target position bailed out capture by the target. The invalid cue's capture, however, required that attention had to be shifted to the target's position when the target had started. Therefore, target-elicited laterality effects during the late time window were compromised in matching valid conditions but not in matching invalid conditions.

2.2.7. Target-elicited laterality effect with non-matching cues

As can be seen from Fig. 6, the non-matching cue was without effect during the early phase, laterality × validity, $F(1, 11) = 1.77$, $p = .21$, and during the later phase, laterality × validity, $F(1, 11) = 1.77$, $p = .21$.

2.2.8. Target-elicited laterality effects – Omnibus ANOVA

The bi-phasic pattern of capture by cues in matching but not in non-matching conditions was also confirmed in an Omnibus ANOVA of the target-elicited activity at PO7 and PO8, with the variables window (early window: 140–200 ms after the onset of the cue; late window: 200–260 ms after the onset of the cue), electrode side (left; right), laterality (contralateral to the target; ipsilateral to the target), matching (matching; non-matching), response congruence (response congruent; response incongruent), and validity (valid: target = cue side; invalid: target ≠ cue side). In this ANOVA, we found a significant four way interaction of window × laterality × matching × validity, $F(1, 11) = 6.41$, $p < .05$, but no higher-order interactions involving this term, Fs < 1.00.

2.3. Discussion

The main result of the present experiment is that when colour singletons are rendered invisible by means of backward masking, only goal-matching singletons capture attention, while non-matching singletons do not. The failure of an invisible colour singleton to capture attention in a stimulus-driven way was revealed by its behavioural cueing effect and its ERP effect. The absence of the N2pc elicited by the non-matching colour singleton cue suggests that quick deallocation was not a major factor in the present experiment with masked singletons. Looking at the lower panel of Fig. 4, one can see that only a very small activity difference be-

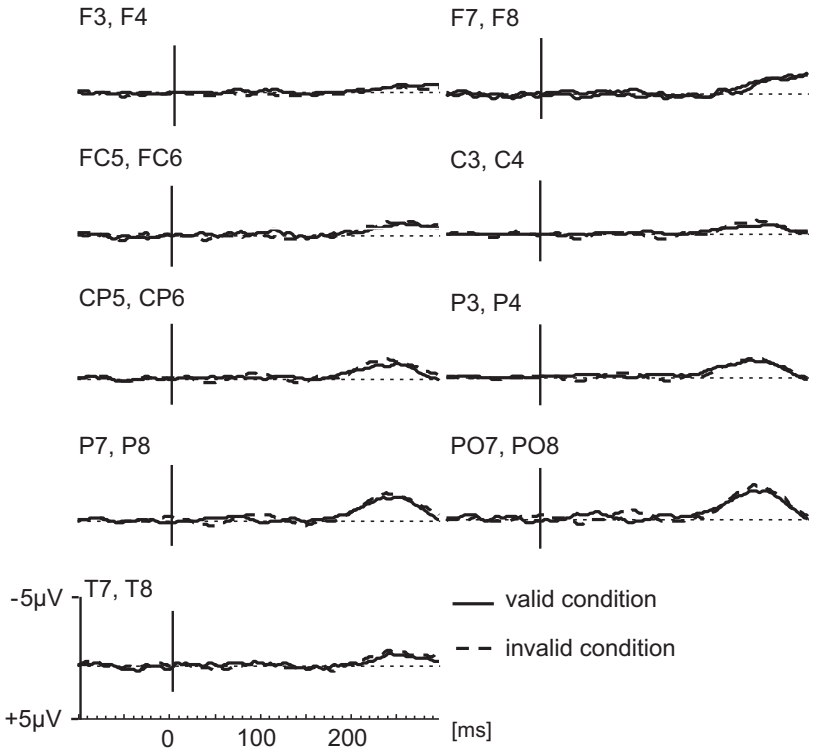

Fig. 6. Activity at electrodes contralateral to the target minus activity at electrodes ipsilateral of the target, separately for different scalp positions, non-matching valid cues (solid lines) and non-matching invalid cues (dashed lines). ERPs are collapsed across left and right, and response-congruent and response-incongruent conditions. Vertical lines at 0 ms indicate cue onset.

tween more negative contra- than ipsilateral PO7/PO8 activity around 200 ms could be considered a very brief attentional capture effect of the non-matching singleton colour cue. The finding that a masked non-matching colour singleton cue failed to capture attention contrasts with the finding that a masked non-matching shape cue captured attention in the study of Ansorge and Heumann (2006). These authors, however, used two flanking bars above and below a rectangle as a singleton cue and found ERP laterality effects in the N2pc range. It is thus possible that masked shape singletons capture stimulus-driven attention more readily than masked colour singletons (cf. Held, Ansorge, & Müller, in press; Zhaoping, 2008). Note, however, that low-level physical differences (i.e., more energy of the cue flanked by additional bars) rather than an attention-related process, might also account for the modification of the ERP in Ansorge and Heumann (2006).

In addition, we found that the masked colour singleton cue captured attention in a goal-dependent fashion. Attentional capture by the matching colour singleton cue was reflected in a behavioural cueing effect, as well as in an N2pc elicited by the cue, with a maximum at PO7 and PO8 (see Fig. 4). This finding nicely supports the conclusions of Woodman and Luck (2003) and Ansorge et al. (2009) who also found that masked singletons or masked colour cues, respectively, elicited an N2pc in a top-down-contingent fashion. It is also in line with Lamme's (2003) claim that goal-directed attention can be applied to stimuli that so far have not reached the level of awareness (and in fact never must reach awareness).

We have not tested whether inter-trial priming might have contributed to what we called a top-down contingent effect of masked goal-matching cues in the present experiment. Kristjánsson et al. (2005) observed that attentional capture by a colour singleton was primed by the colour singleton in the previous trial, even under conditions in which their two neglect patients failed to see the target in the preceding trial. Such awareness-independent inter-trial priming could have possibly contributed to the capture effect of the masked matching colour singleton cues of the present study because the matching cue had the same colour as the preceding target. By contrast, a non-matching cue had always a colour different from that of the preceding target.

We cannot rule out that inter-trial priming of capture thus contributed to the findings in the present experiment's goal-matching conditions. We think it is an unlikely explanation of the capture effect. In a previous study with backward masked goal-matching colour non-singleton cues, no such inter-trial priming effects were observed although these would have been possible (cf. Ansorge et al., 2009). However, we additionally tested this possibility in Experiment 2.

In the present experiment, no response congruence effect of the masked cues could be found. This finding would be in line with Hamker's (2005) computational theory. Hamker argued that under visual search conditions, with a high uncertainty about the target location, response activation effects could be restricted to the recurrent processing phase, in which activity from cortical frontal areas feeds back on activity in posterior parietal cortex. This phase of visual processing, however, is exactly what is blocked by masking (cf. Lamme & Roelfsema, 2000; Vath & Schmidt, 2007).

Another intriguing finding concerned the colour singleton cue detection performance. As expected on the basis of the low visibility of the masked singleton cues, with the exception of one participant that approximately met the frequency of matching colour singleton cues by his rate of nogo responses, participants' rates of nogo responses were lower than the factual probability of the matching singleton colour cues. This finding accords with a qualitative difference between processing of visual stimuli in aware vs. unaware modes: while participants use the frequencies of stimuli of which they are aware to adjust their behaviour, they fail to adjust their behaviour to the frequencies of stimuli of which they are

not aware (cf. Ansorge et al., 2002; Cheesman & Merikle, 1985; Dixon, 1971). The current findings showed that in line with this qualitative difference between aware and unaware processing modes, participants failed to represent the frequencies of the stimuli of which they were not aware. In addition, d' was very low. This also testified that the participants' awareness of the masked colour singleton cues was effectively prevented to large extents. Also corroborating the conclusions, the combined cue-detection/target discrimination task of the present study provided a conservative measure of the masked singleton colour cue's effect: Combining the cue-detection and target-search tasks in a single block allowed us to eliminate those trials in which observers actually indicated seeing a masked goal-matching colour singleton. Finally, numerically the correlation between d' and RT validity effect scores was low.

3. Experiment 2

In Experiment 2, we again tested whether stimulus-driven capture by an irrelevant non-matching singleton colour cue is prevented under masked conditions with little awareness about the cues. In addition, we once more tested in a control condition whether a masked goal-matching colour singleton cue can capture attention. This time, however, we made sure that the effect was not better explained by colour priming. To that end, we used two target colours but only one colour for the matching cues. As a consequence, matching cues were either colour-congruent, that is, similar to the preceding target (or the subsequent target), or colour-incongruent, that is, dissimilar to the preceding target (or the subsequent target). If the cueing effect of the masked matching cue reflected only contingent capture dependent on a match between cue colour and top-down search template, the same size of cueing effect was expected under colour-congruent and -incongruent matching conditions.

We also used the matching conditions for a more exhaustive test of the singleton's stimulus-driven effects under masked conditions. We used two kinds of matching colour cues, singleton cues (as in Experiment 1) and non-singleton cues. In cases, in which participants seemingly adopt a colour-search mode an additional singleton capture effect can sometimes be observed, too (Lamy & Zoaris, 2009). Therefore, it could be that the effect of a masked goal-matching colour cue is at least stronger if it is a singleton cue than if it is a non-singleton cue. We tested only behavioural cueing effects. No ERPs were recorded. Also in contrast to Experiment 1, cue visibility was tested in a separate block after the target search task rather than in the same block.

3.1. Method

3.1.1. Participants

Thirty-two volunteers (29 female) with a mean age of 24 years participated.

3.1.2. Stimuli and procedure

See also Fig. 7 for a depiction of an example of a trial. Methods were as in Experiment 1 with the following exceptions. In each trial, four circular cues were shown. In the target search task, participants searched for two target colours either green and blue targets, green and red targets, or red and blue targets, with the relevant colours balanced across participants. Per each participant, fifty percent of the trials contained a target of one colour and fifty percent contained a target of the other colour.

For half of the participants, the cue was a singleton of one of two colours. The singleton colour cue was goal-matching if it had one of the target colours. Because singleton cue colour and target colour were uncorrelated across trials, even the matching singleton cue was colour similar to the targets in only half of the matching trials. It was colour dissimilar to the target in the other half of the matching trials. In addition to the matching cues, we used non-matching cues. These had one of the remaining distractor colours. The positions of masked singleton colour cue and of target were uncorrelated. As a result, we got 25% valid and 75% invalid conditions.

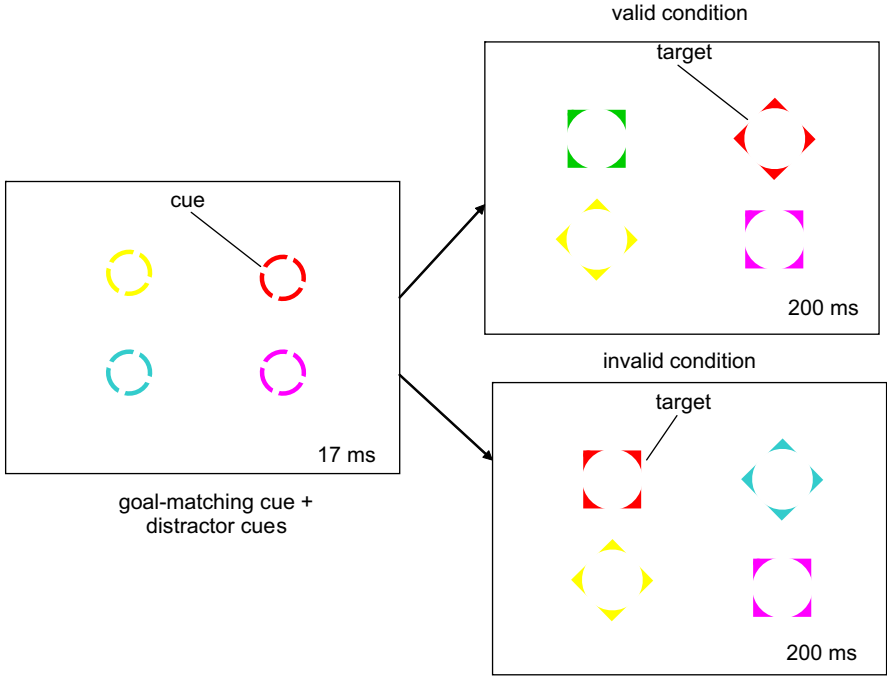

Fig. 7. Depicted are examples of a goal-matching cue display on the left and target displays on the right, with an example of a valid trial (upper corner) and an example of an invalid trial (lower corner) of Experiment 2's non-singleton-cue conditions. For further details refer to the method section. Stimuli are not drawn to scale.

For the other half of the participants, the cues were non-singletons. In the non-singleton-cue conditions, everything was the same as in the singleton-cue conditions, except for a random colouring of three of the circular cues with three different colours. As a consequence, the non-matching cue in the non-singleton conditions was not standing out among its concomitant distractors in any particular way. Hence, it should not capture attention. However, for the sake of a comparison between the matching cue's capture effect under singleton-cue and non-singleton-cue conditions, one dummy non-matching non-singleton colour cue was chosen per participant that was also exactly 25% valid and 75% invalid.

The target search task consisted of five blocks, each with two repetitions of two target colours × four cue positions × four target positions, altogether 64 trials. The colour cue-detection task consisted also of five blocks and was the same but for the task. In the colour detection task, participants had to search for the matching colour cue and had to report in each trial whether it was present or absent. Participants always started with the search task and concluded with the detection task.

3.2. Results

3.2.1. Search for visible targets

See Figs. 8 and 9, and Tables 3 and 4 for the results of the target search task in Experiment 2. Out of all trials, 2.5% were rejected because responses were faster than 100 ms or slower than 1500 ms. We first tested whether in the matching trials cue-target colour congruence (cue colour = target colour vs. cue colour ≠ target colour) affected the performance, or whether collapsing across matching colour-congruent and colour-incongruent cue-target conditions would be okay. Only for the matching conditions, an initial ANOVA of the mean correct RTs with the within-participant variables validity (valid vs. invalid), cue-target colour congruence (cue colour = target colour vs. cue colour ≠ target colour), and the between-participants variable cue type (singleton cue vs. non-singleton cue) was conducted. This ANOVA revealed neither a significant main effect of cue-target colour congruence nor any significant interaction with that variable, all Fs < 1.00. For subsequent analyses, data were collapsed across colour-congruent and colour-incongruent conditions.

Correct responses, subjected to a repeated-measures ANOVA with the within-participant variables validity (valid vs. invalid) and matching of the cue (matching vs. non-matching cue), and the between-participants variable cue type (singleton vs. non-singleton cue), showed a significant main effect of validity, $F(1, 30) = 5.01$, $p < .01$, and a significant validity × matching interaction, $F(1, 30) = 8.90$, $p < .01$. Responses were faster under valid (RT = 708 ms) than under invalid (RT = 719 ms) conditions. However, the interaction reflected that the cueing effect was restricted to the matching conditions (valid RT = 703 ms; invalid RT = 726 ms), $t(31) = 3.79$, $p < .01$. No cueing effect was found in the non-matching conditions (valid RT = 713 ms; invalid RT = 712 ms), $t < 1.00$.

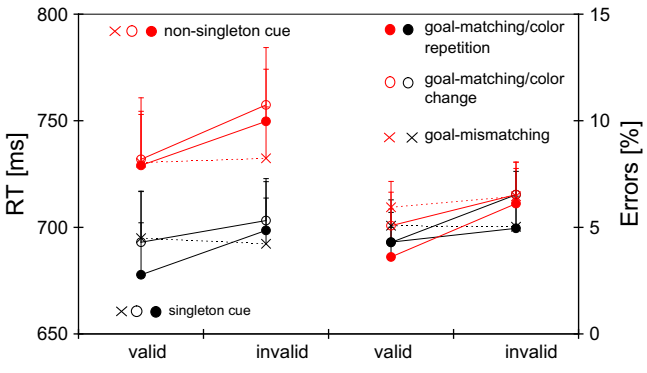

Fig. 8. Mean reaction times (RTs) on the left and mean percentages of errors on the right of Experiment 2's target search task as a function of the type of cue (red symbols: singleton cue; black symbols: non-singleton cue), the goal-matching of the cue (round symbols: goal-matching versus crosses: non-matching), priming (filled circles: colour repetition vs. clear circles: colour switch), and cue-target distance (valid vs. invalid). Bars depict standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

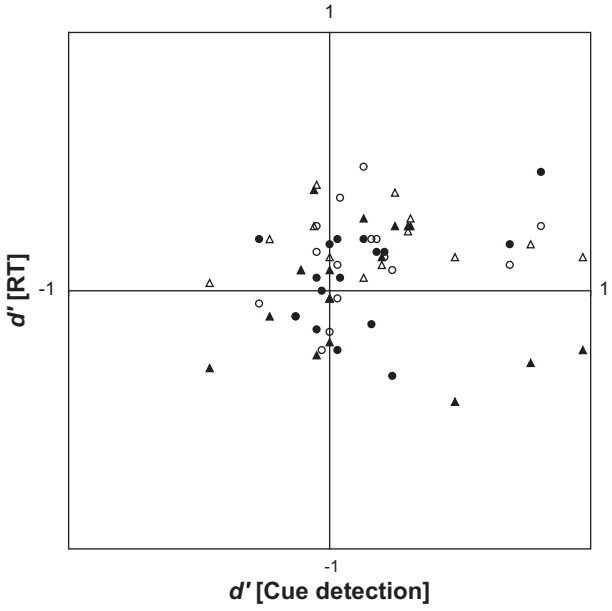

Fig. 9. Individual cueing effects in target search reaction times (expressed as d' [RT]) of the goal-matching colour cue (open circles and triangles) and of the not-matching colour cue (filled circles and triangles) as a function of cue visibility measured in a cue-detection task (expressed as d' [cue detection]) and of cue type (singleton cue: circles; non-singleton cue: triangles) in Experiment 2 (data from 32 participants; 16 per cue type condition).

In a subsequent ANOVA of only the matching conditions, with the within-participant variables validity (valid vs. invalid), inter-trial priming (colour repetition vs. colour switch relation between preceding target and current cue), and the between-participants variable cue type (singleton cue vs. non-singleton cue), neither a main effect of priming, nor a significant validity × priming interaction, nor a significant three-way interaction was found. With the exception of the validity effect, $F(1, 30) = 12.32$, $p < .01$, all tests were non-significant, Fs < 1.00. Additional t tests confirmed a cueing effect in colour switch trials (valid RT = 712 ms; invalid RT = 730 ms) as well as in colour repetition trials (valid RT = 704 ms; invalid RT = 724 ms), both ts(31) > 1.82, both ps < .05, one-tailed.

An ANOVA of the arc-sine transformed error rates (ERs) with the variables validity, matching, and cue type showed a significant main effect of validity, $F(1, 30) = 12.84$, $p < .01$, with a lower error rate in valid (4.88%) than invalid (5.90%) conditions. The validity × matching interaction was almost significant, $F(1, 30) = 3.03$, $p = .09$. It reflected stronger validity effects in matching (valid ER = 4.3%; invalid ER = 6.1%) than in non-matching conditions (valid ER = 5.5%; invalid ER = 5.7%). Cueing effects in ERs of the matching conditions were about the same in colour repetition (valid ER: 3.96%; invalid ER: 5.53%) and colour switch conditions (valid ER: 4.69%; invalid ER: 6.53%), and both these cueing effects were significant, ts(31) > 2.70, both ps < .05. This was also reflected in an additional ANOVA of the arc-sine transformed error rates of only the matching conditions with the variables validity (valid vs. invalid), priming (colour repetition vs. colour switch relation between

Table 3
Individual performance in cue detection (d'), and during target search (d'_{RTs}, Cohen's d RTs, RT cueing effect, and mean ranked RT cueing effect) as well as means across participants and t values (tested against Null), separately for matching cues (on the left) and non-matching cues (on the right) in Experiment 2's singleton-cue conditions.

	d' (as non-matching)	d'RT	Cohen's d RT	RT cueing effect	Mean ranked RT cueing effect	d' (as matching)	d'RT	Cohen's d RT	RT cueing effect	Mean ranked RT cueing effect
1	0.03	0.10	0.18	29	7.30	0.03	0.20	0.04	6	8.62
2	0.18	0.20	−0.04	−6	3.34	0.18	0.15	0.17	27	14.79
3	0.21	0.13	0.21	29	11.22	0.21	0.15	0.16	20	8.11
4	0.81	0.25	0.07	11	17.40	0.81	0.46	0.41	47	30.61
5	−0.05	0.25	0.05	9	6.25	−0.05	−0.15	−0.05	−7	−5.84
6	−0.13	−0.10	−0.11	−21	−14.16	−0.13	−0.10	0.04	8	0.55
7	−0.05	0.15	0.38	58	30.36	−0.05	0.05	0.22	37	11.92
8	−0.27	−0.05	−0.06	−6	−2.63	−0.27	0.20	0.29	31	24.83
9	0.00	−0.16	−0.04	−8	1.32	0.00	0.18	−0.32	−59	−13.80
10	0.13	0.48	0.22	37	19.19	0.13	0.20	0.19	37	14.87
11	0.03	−0.03	0.03	6	4.48	0.03	−0.23	−0.12	−18	−18.49
12	−0.03	−0.23	−0.04	−7	−13.14	−0.03	0.00	0.10	20	2.93
13	0.04	0.36	0.21	48	23.61	0.04	0.05	−0.13	−27	1.72
14	0.69	0.10	0.12	12	16.93	0.69	0.18	0.03	4	9.83
15	0.24	0.08	0.00	1	1.67	0.24	−0.33	−0.22	−49	−14.11
16	0.16	0.20	0.12	21	15.38	0.16	−0.13	−0.17	−33	−8.13
Mean	0.12	0.11	0.08	13	8.03	0.12	0.06	0.04	3	4.28
$t(15)$	1.79	2.31	2.46	2.39	2.61	1.79	1.11	0.82	0.34	1.23
p	.10	.04	.03	.03	.02	.10	.29	.43	.74	.24

Table 4
Individual performance in cue detection (d'), and during target search (d'_{RTs}, Cohen's d RTs, RT cueing effect, and mean ranked RT cueing effect) as well as means across participants and t values (tested against Null), separately for matching cues (on the left) and non-matching cues (on the right) in Experiment 2's non-singleton-cue conditions.

	d' (as non-matching)	d'RT	Cohen's d RT	RT cueing effect	Mean ranked RT cueing effect	d' (as matching)	d'RT	Cohen's d RT	RT cueing effect	Mean ranked RT cueing effect
1	0.13	0.05	0.02	3	5.09	0.13	0.28	0.30	63	16.73
2	−0.11	0.08	0.14	27	15.87	−0.11	0.08	−0.04	−6	2.82
3	0.20	0.10	0.29	46	23.22	0.20	0.13	0.23	41	18.59
4	0.00	0.13	0.14	20	12.52	0.00	0.08	−0.23	−31	−8.99
5	0.77	0.18	0.07	10	2.01	0.77	−0.28	0.20	32	−4.55
6	−0.23	0.20	0.13	20	12.84	−0.23	−0.10	−0.32	−40	−20.82
7	−0.46	0.03	0.06	11	−3.45	−0.46	−0.30	−0.12	−27	−18.36
8	0.25	0.38	0.42	103	27.42	0.25	0.25	0.20	46	12.66
9	0.31	0.28	0.12	20	21.25	0.31	0.25	−0.10	−15	3.17
10	−0.06	0.25	0.11	21	5.52	−0.06	0.39	0.19	38	15.85
11	0.48	0.13	0.02	4	6.91	0.48	−0.43	0.01	3	−6.40
12	0.30	0.23	0.37	61	30.97	0.30	0.25	0.26	35	17.61
13	0.97	0.13	0.01	1	3.84	0.97	−0.23	−0.26	−38	−12.77
14	0.00	−0.03	−0.11	−25	−5.08	0.00	−0.20	−0.11	−26	−7.74
15	−0.05	0.41	0.13	26	28.84	−0.05	−0.25	−0.05	−9	−11.32
16	0.00	−0.03	−0.02	−4	0.33	0.00	−0.03	−0.15	−27	−4.28
Mean	0.16	0.16	0.12	22	11.76	0.16	−.01	.001	2.42	−0.49
$t(15)$	1.71	4.83	3.38	2.93	4.02	1.71	-0.12	.029	0.28	−0.15
p	.11	.001	.004	.01	.001	.11	.91	.98	.78	.89

preceding target and current cue), and cue type (singleton cue vs. non-singleton cue), in which all interactions and main effects but the main effect of validity, $F(1, 30) = 15.14$, $p < .01$, were far from significant, all other Fs < 1.60, all other ps > .20.

3.2.2. Colour cue detection

Again, none of the participants reported having seen the masked colour cues. Mean d' values were again low, and the results thus suggested a low colour cue visibility and very good masking, $d' = 0.12$, $t(15) = 1.79$, $p = .10$, for the singleton colour cues, and $d' = 0.16$, $t[15] = 1.71$, $p = .11$, for the non-singleton colour cues. See also Tables 3 and 4 and Fig. 9.

3.2.3. Cue detection and target search

The d'_{RT} score (analogue to the RT cueing effect in the target search task) was 0.11 in matching/singleton colour cue conditions and significantly differed from zero, $t(15) = 2.31$, $p < .05$. It was 0.16 in matching/non-singleton colour cue conditions, and again significantly different from zero, $t(15) = 4.83$, $p < .01$. These d'_{RT} scores were not significantly correlated with the d' scores from the colour cue-detection tasks, both rs(16) < .34, both ps > .20 (see also Fig. 9). This was also true if the correlation was calculated for a larger sample across singleton and non-singleton cues, $r(32) = .24$, $p = .19$.

Again, we also correlated individual d' values from the colour cue-detection task with three alternative individual measures of the RT cueing effect during the target search task (see also Tables 3 and 4), a simple RT cueing effect, both rs(16) $\leqslant$ .10, $p \geqslant .74$ (across groups: $r[32] = .05$, $p = .80$), *Cohen's d* of the RT cueing effect, both rs(16) $\leqslant$ .16, $p \geqslant .56$ (across groups: $r[32] = .07$, $p = .70$), and the mean RT rank validity difference, both rs(16) $\leqslant$ .40, $p \geqslant .12$ (across groups: $r[32] = .20$, $p = .27$). All of these measures led to the same conclusion: there was no significant correlation between colour cue detection performance and RT cueing effect.

3.3. Discussion

Colour cue detection performance was slightly better in the present experiment. This can be seen on the abscissa of Fig. 9.

Yet, the correlation between d' and d'_{RT} was again relatively low and non-significant. In addition, the low residual correlation that we found might in fact have rather reflected that the colour cue-detection task was now actually drawing on processes that are independent of awareness, just as the cueing effect of the matching cue. This, at least, is the risk of using an exhaustive measure in the visibility test: that the measure is no longer exclusively sensitive for the contributions of awareness but picks up awareness-independent processing (cf. Reingold & Merikle, 1988).

Again, Experiment 2 demonstrated that stimulus-driven capture by the masked singleton cues depends on the singleton's visibility because with the masked cues no validity effect was found in the non-matching conditions. As in Experiment 1, this null finding contrasted with validity effects in various control conditions, with goal-matching cues. In addition, even in the matching condition, the cue's capture effect was not influenced by the singleton status of the masked cue. We found the same cueing effect of matching colour cues, regardless of whether these were non-singleton or singleton cues. This means that the singleton status of the cue also failed to boost the cueing effect of the matching cues.

In addition, we secured that the goal-dependent cueing or validity effect of the matching cues in the control conditions truly reflected attentional capture. This conclusion was supported by two arguments. First, the goal-dependent cueing effect was found, regardless of the colour of the visible target preceding the masked matching cue. Therefore, inter-trial priming (cf. Belopolsky et al., 2010; Maljkovic & Nakayama, 1994) cannot explain the matching colour cue's capture effect. Second, the goal-dependent cueing effect was not affected by the colour congruence of cues and targets within the same trial. Therefore, within-trial colour priming can also not account for our findings in the goal-matching control conditions and the results are therefore in line with other studies showing contingent attentional capture by masked stimuli (e.g., Ansorge et al., 2009; Woodman & Luck, 2003).

Besides, the present experiment used circular cues. These had no similarity to the response-relevant angular shapes of the targets. Therefore, our results showed that attentional capture by masked matching colour cues does not crucially hinge on the response relevance of these features. In that respect, capture by the masked colour cue operates as capture by clearly visible colour cues (cf. Folk et al., 1992).

4. General discussion

According to stimulus-driven or bottom-up theories of visual attention (cf. Itti & Koch, 2001; Parkhurst et al., 2002), colour singletons could be capturing attention in a stimulus-driven manner even if masked: the reason is that computational bottom-up theories compute local colour differences merely on the basis of objective stimulus features measurable in the image, such as the normalised standard deviation of colour values in a circumscribed patch (e.g., Frey et al., 2008), for assessment of an image region's potential to capture attention. However, the current study suggested that awareness of the singleton – that is, subjective or phenomenal salience rather than an objective feature difference is responsible for bottom-up capture by a colour singleton. This conclusion nicely fits prior results. Several lines of evidence testified that colour differences might exert their stimulus-driven attentional capture influences by means of phenomenal awareness. Stimulus-driven capture of the eyes by colour contrast in 2-D images during free-viewing of natural scenes, for instance, depended on shapes or spatial frequencies as contextual input: Frey et al. (2008) found evidence for a stimulus-driven effect of red–green contrasts on fixation probabilities only in images depicting tropical forests. In fractals, by contrast, the same red–green colour contrast failed on a number of criteria of stimulus-driven capture. This means that visual context provided by orientation, shape, or spatial frequency features within the image crucially modified the stimulus-driven capture by colour contrast. This context effect is also a clear indication that the colour contrast's capture effect requires phenomenal awareness because on a physiological level contextual influences on cell activity in early visual areas are successfully suppressed by masking (cf. Supèr, Van der Togt, Spekreijse, & Lamme, 2003; Zipser, Lamme, & Schiller, 1996). Other studies are thus in line with this conclusion. In natural images, colour contrasts might be rarely exploited early during visual detection: instead colour contrast seemingly has its major impact later for the successful retrieval from memory (Yao & Einhäuser, 2008). This outlined scheme of a late colour difference effect on attention is perfectly in line with the generally known impacts of shape, orientation, or spatial frequency on phenomenal colour representation (cf. Hansen, Olkkonen, Walter, & Gegenfurtner, 2006).

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